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HIGH-TEMPERATURE CERAMICS FOR AUTOMOBILE GAS TURBINES

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Peter Walzer

1. Introduction

The advantages of automobile gas turbines proven up to now were /1* mainly low pollutant emissions, and also the fact that the powerplants can be operated with a very broad spectrum of different fuels. On the other hand, up to now the fuel consumption of this alternative type of drive is higher or at best equal to that of the internal combustion engine. As regards production costs too, today's automobile gas turbines are much more costly than the conventional piston engines. The problems of fuel consumption and the manufacturing costs may however be solved it seems at least partially, if in the future it is possible to increase the turbine input temperature in these propulsion units to 1500 to 1600 K. The metal alloys used up to now on the other hand only permit temperatures up to 1300°K. It seems hardly possible to achieve effective blade cooling because of the complication and the additional costs involved. Hence elements made of new non-metal materials are required which are able to withstand these higher working temperatures.

The purpose of a Volkswagen research project is to develop elements made of ceramic materials such as Si_3N_4 or SiC and thus assure the prerequisites for a later high temperature gas turbine. These studies are part of a comprehensive ceramic development program, which was carried out by various vehicle and ceramic manufacturers, sponsored by the Federal Ministry for Research and Technology.

Fig. 1 shows one of the possible designs of a high temperature automobile gas turbine. The ceramic elements include the combustion

* Numbers in margin indicate foreign pagination

chamber, the turbine guide-vane rings, the turbine wheels as well as the heat exchanger and the various heating gas conduits. After consultations with other car manufacturers taking part in the ceramics program, Volkswagen is concentrating on the development of combustion chambers, turbine guide-vane rings and turbine wheels. In this connection, Volkswagen is carrying out mainly the component designs and testing, while the actual manufacture of the components is being carried out by ceramic manufacturers such as Annaweke, Degussa, Feldmuehle, Norton or Rosenthal. /2

The author already presented in detail in /1/ the prospects of a high-temperature gas turbine, the design of such a propulsion unit as well as the qualities of the ceramic materials and the calculation and layout of the components. A report will now be given on the development level reached today after about three years of this research program have elapsed.

2. State of Development of the Components

2.1. Combustion Chamber

Because of its function, the latter should have a thin wall and a large volume. In the reaction area, the wall temperature may reach 1800°C. Since between reaction zone and gas outlet there may be a considerable difference in temperature, temperature gradients of 50 K/mm may arise along the fuel chamber wall. Furthermore one should exclude temperature shocks in cold starting and hot disconnection.

In the course of the research program various ceramic materials and methods of manufacture of this component were studied. Among the materials Si-infiltrated SiC proved to be particularly good for this application. Fig. 2 shows the SiC combustion chambers in various manufacturing processes. The combustion chamber shown on the left was manufactured in the slip-casting method. The combustion chambers shown in the center and on the right were pressed isostatically from two versions of material. Some of the combustion chambers have withstood the stationary and non-stationary operating conditions of the present 1300 K gas turbines and reached operating times of 20 hours. /3

2.2 Turbine Guide-Vane Rings

The turbine guide-vane rings of a high temperature automobile gas turbine should be able to withstand average gas temperatures up to 1600 K. Unevennesses in the temperature distribution around this average value cannot be excluded. In addition the thin blade profiles may be exposed to changes in the gas temperatures up to 500 K/s. Finally the manufacture of the complicated blade profiles with rear edge radii < 0.5 mm also represents a critical requirement.

Fig. 3 shows different designs of the ceramic guide-vane ring. On the left, individual blades are connected with an external ring through inserts. In the center and on the right designs are shown, in which the guide-vane ring is assembled in different types of individual blades in the internal and external rings. The material is each time reaction sintered Si_3N_4 . The blades are produced by injection molding, the rings by isostatic pressing.

Fig. 4 shows a guide-vane ring at an average gas temperature of 1650 K and a temperature distribution of ± 300 K. Guide-vane rings which were assembled in the described manner from individual blades and rings had reached by the end of the first phase of the program a total testing time of about 5 hours in stationary and non-stationary operation. Furthermore a large number of thermal shocks were withstood without damage.

2.3 Totally Ceramic Turbine Wheel

The results obtained in the first phase of the program with pre- /4 dominantly static stress of the components are highly promising. The question as to whether a high temperature gas turbine on a ceramic base can be developed is mainly decided by the turbine wheel. Fig. 5 shows in the central diagram the tensile stresses appearing in the wheel 30 seconds after a cold start. According to it the stresses at the base of the blade are 110 N/mm^2 and in the bore of the hub 400 N/mm^2 .

The component temperature is 1500 K in the blades and 1300 K in the hub. Under these conditions the blades should not creep by more than 1% in 300 hours.

According to the level of the modern material technology, only hot-pressed Si_3N_4 has the high strength required in the hub and only reaction-sintered Si_3N_4 has sufficiently low creep rates and good shaping capacity needed in the blades. Hence a completely ceramic wheel should be made of these two versions of material.

Fig. 6 shows different development designs of such a wheel. In design A the reaction sintered blade ring, and the hub, starting from Si_3N_4 powder is hot-pressed into this blade ring. It is known that this method will permit high bonding strengths to be achieved. However, it is still unclear how far the reaction-sintered blades are damaged during the hot pressing. In design B the complete rotor is pre-fabricated by the reaction sintering method, and then attached in the hub area in a subsequent hot-pressing method. In this design the bonding ^{/5} of two different materials is avoided. However, the strength obtained by subsequent hot-pressing of a reaction-sintered component may not be sufficient. For the two designs C and D both the blade ring and the hub are pre-fabricated. Bonding will be achieved through a cement at moderately high temperatures and pressures. The main problem is the exact geometrical adjustment of the components to be bonded.

Fig. 7 shows the development steps of each of these concepts during the first program phase. A hot-pressed hub is shown on the left side, and its high strength must first be assured. The center of the picture shows this hub connected to a simple, reaction-sintered ring, which was used to investigate the quality of the connection. The right side shows the smooth ring replaced by a simple scoop wheel which was used to carry out simplified strength and thermal shock tests.

In the previous research program, studies of strength were carried out mainly as cold centrifuge tests. As shown in Fig. 5, the stresses which might occur in the hot operation of such a rotor can be simulated satisfactorily by cold centrifuge tests with high numbers of revolution. Fig. 8 shows a composite rotor at the time of rupture. In this case the break starts obviously from a point in the neck area of the hub. As a result of the previous phase of the program it was possible to develop hot-pressed hubs which reach the required number of revolutions of 112,000 ¹/minute with a survival probability of 1 to 2. With bound

prototype wheels peripheral speeds of 450 m/s were obtained referred to the external diameters. In thermal tests it was possible to prove that these rotors can withstand at least a limited number of cycles without damage.

Fig. 9 shows the level of development which was achieved with /6 totally ceramic wheels at the end of the first phase of the ceramics program. Further great efforts are needed before it can be evaluated, whether there are prospects on arriving with the adopted method to totally ceramic wheels which are functional and can be manufactured economically.

2.4 Metal-Ceramic Turbine Wheel

Because of the high production risks of the totally ceramic wheel the development program was extended to the design of a wheel with metal hub and ceramic blades. With this design, in the less warm hub region one may utilize the higher tensile strength of the metal alloy whereas in the region of high gas temperatures but lower stresses ceramic blades may be used. Because of the low thermal strength of the metal hub, in this design the gas temperatures had naturally to be 100 K lower. Furthermore in a small wheel only a small number of blades can be used so that a decrease of efficiency may be expected.

Fig. 10 shows such a rotor. With injection cast Si_3N_4 blades in cold centrifuge tests peripheral speeds referred to the external diameter were obtained of 480 m/s. In thermal shock cycles, such rotors have withstood several hundred cycles with gas temperature changes of up to 600 K/s without damage.

3. Summary and Future Main Working Points

As a result of the first phase of development a level was reached which would permit beginning the development of concrete components for stationary components such as gas conduits, flame tube of the combustion chamber and turbine guide blades. Individual very good results /7 were also obtained with rotors with metal hub and ceramic individual blades. However in future further efforts must be made in the area of development of components to reduce the spread of component strength by suitable improvement of the material, the method of manufacture and

the testing method. This wheel design seems to be promising with regard to obtaining a solution compatible with economy. As mentioned above, however, some defects should be eliminated with regard to the permissible gas temperature and the achievable efficiency.

As was expected even at the beginning of the study, the development of a completely ceramic wheel is the most difficult problem to solve. In the course of the research program implemented to date it was possible to develop hot-pressed hubs with sufficient strength. Various designs were studied for the connection with the reaction-sintered blade ring. Some of these designs gave very promising partial results, but they are not sufficient to permit in principle the statement that it may ever be possible to produce a totally ceramic turbine wheel economically. Further studies should concentrate on this problem.

REFERENCES

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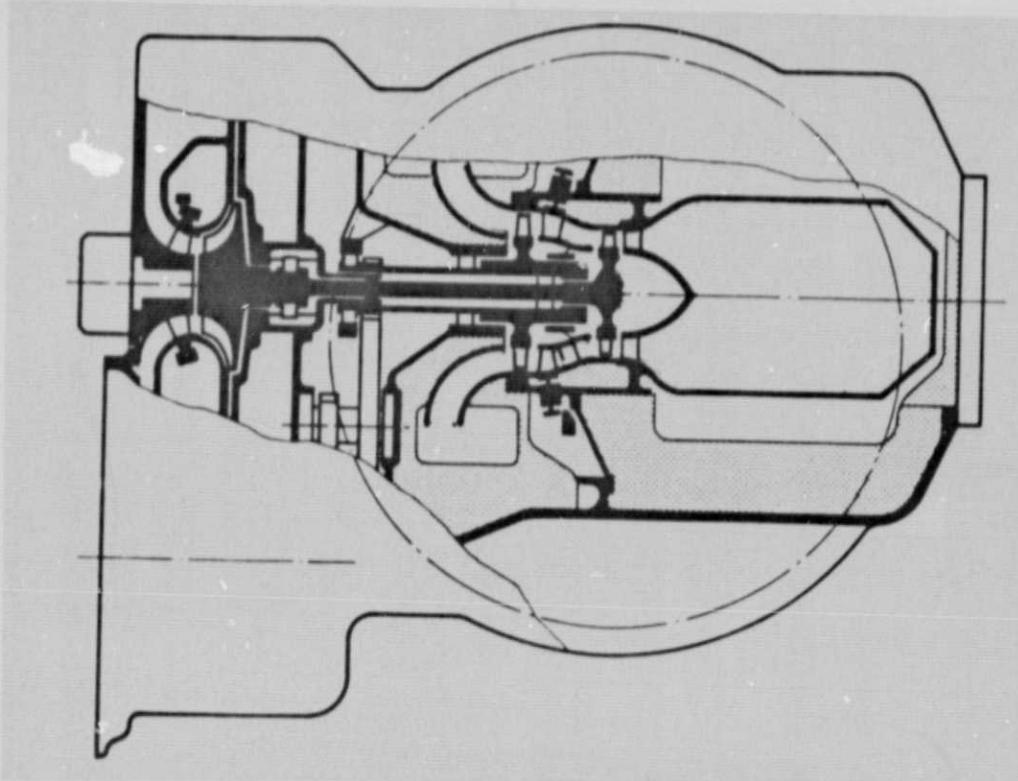
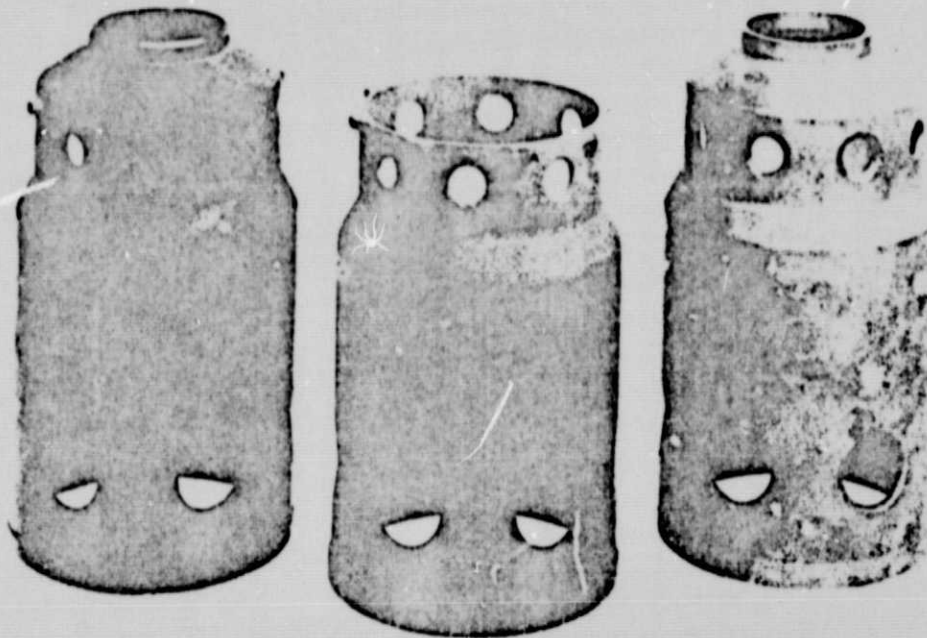


Figure 1: Ceramic gas turbine*
*Drafting instructions omitted.

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Infiltrated SiC
Slip-cast

Pure SiC mullite
Impregnated
Isostatically pressed

REFEL -
Infiltrated SiC
Isostatically pressed

Figure 2: SiC combustion chambers

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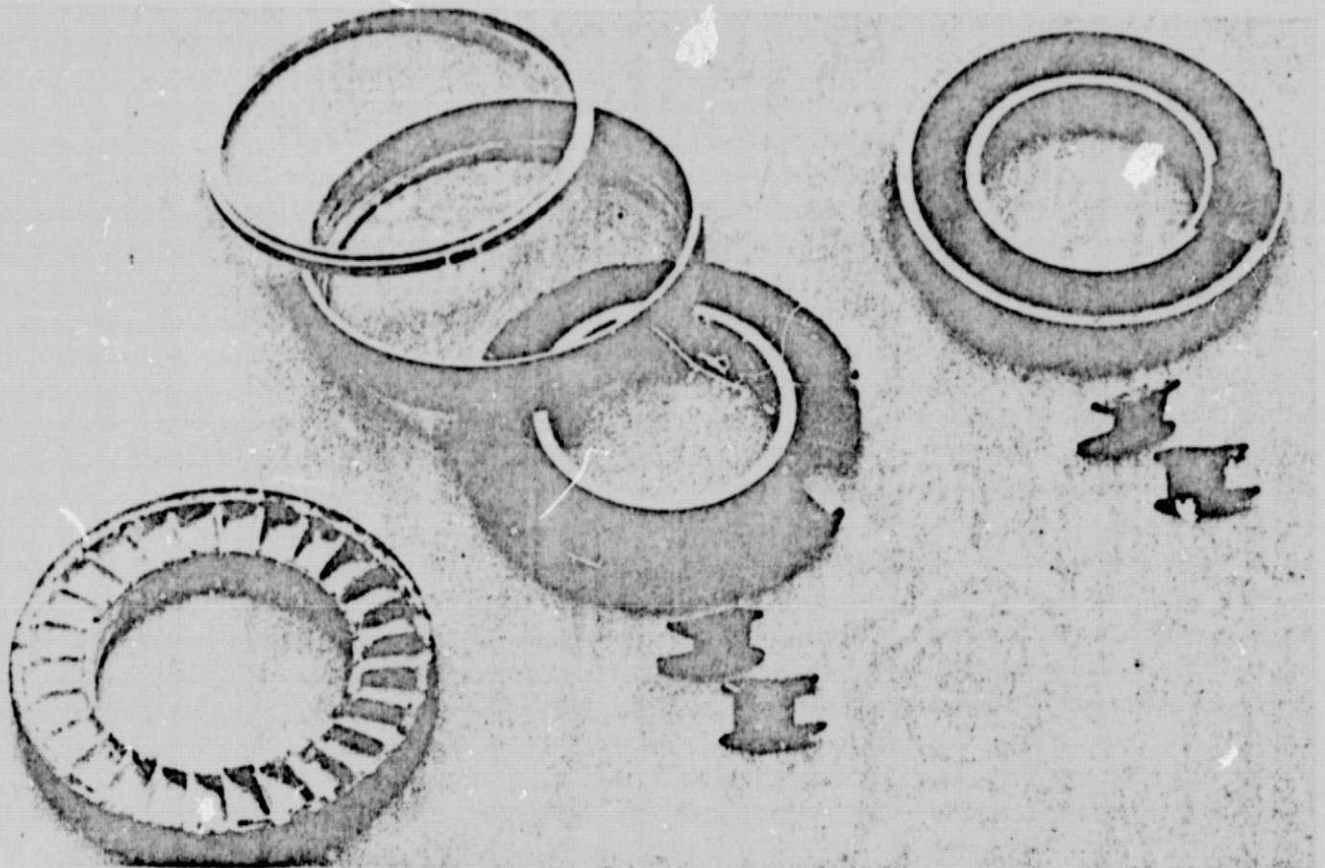


Figure 3: Si₃N₄ Turbine Stator Assemblies

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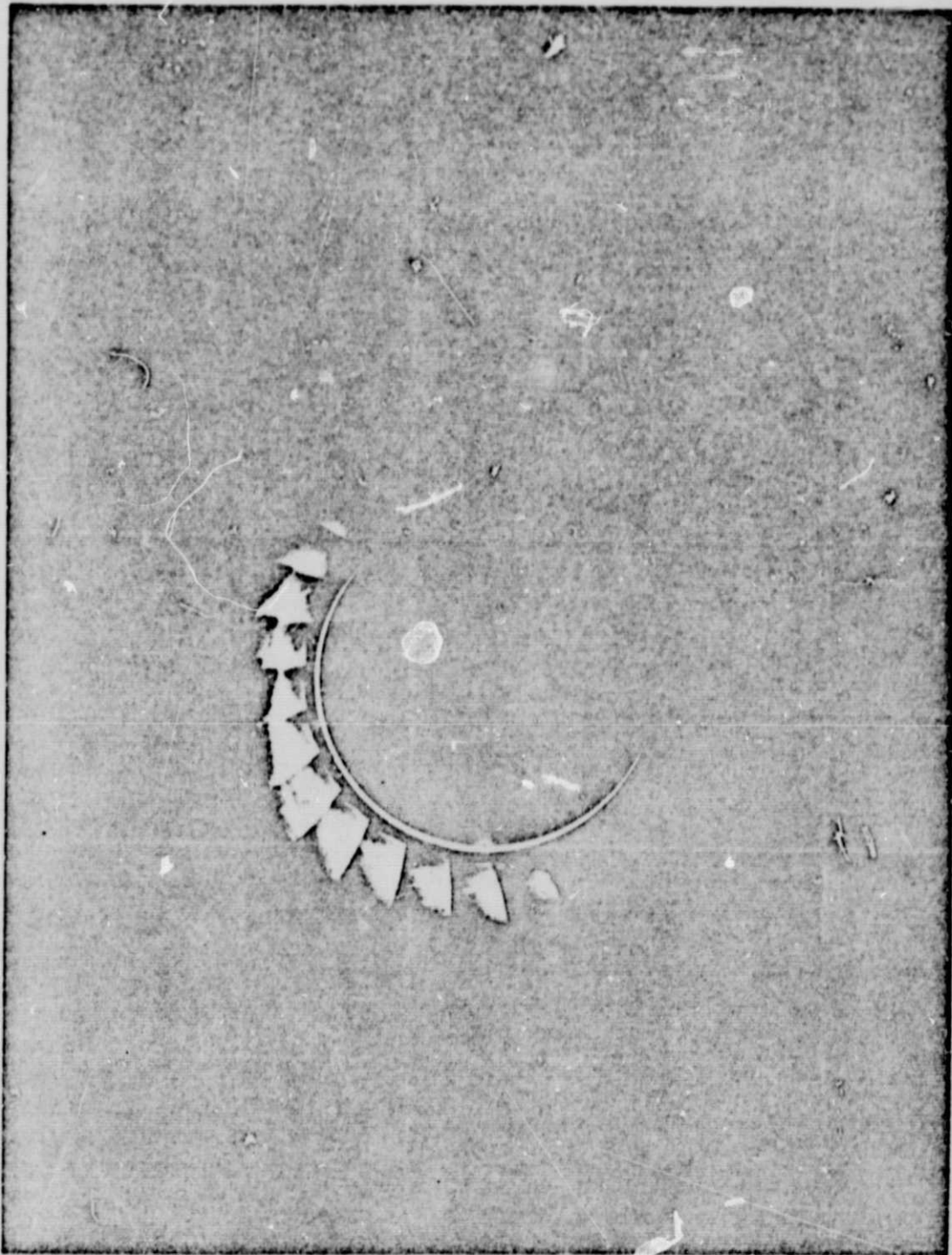


Figure 4: Turbine Guide Vane Ring of RBSN at 1650 K

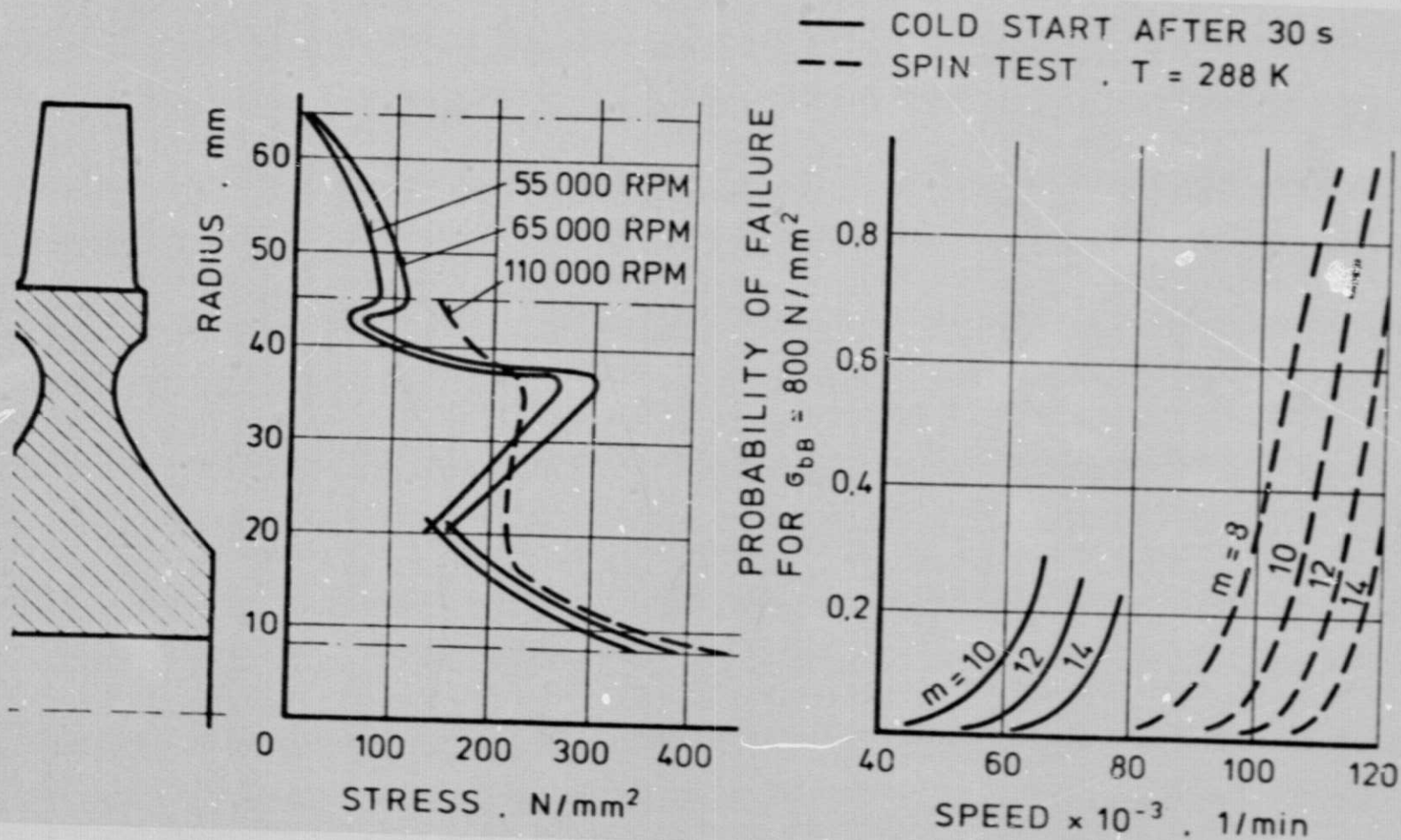


Figure 5: Rotor Stresses and Probability of Failure*
 *Drafting instructions omitted.

For diameter 5 x 5 cm
Masker section 25 x 35 mm

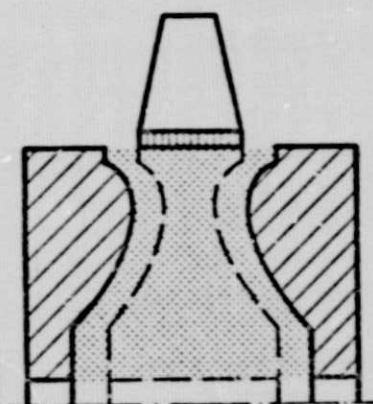
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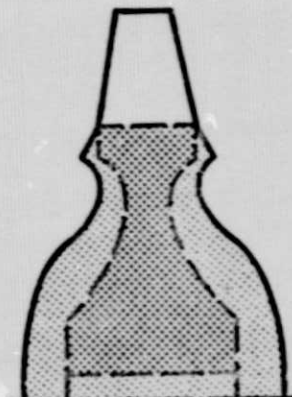
See also VW 510 34



DESIGN A

RBSN blade ring

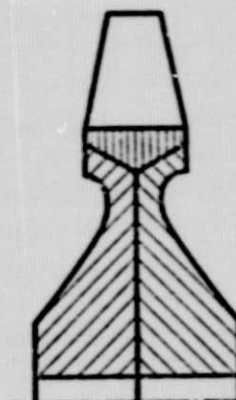
Disk of hot pressed
HPSN powder



DESIGN B

RBSN turbine wheel

Gradually post
hot pressed

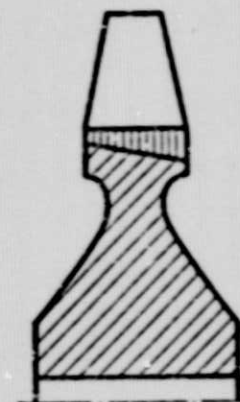


DESIGN C

RBSN blade ring

Prefabricated HPSN
disk halves

Cement bonding



DESIGN D

RBSN blade ring

Prefabricated HPSN
disk halves

Cement bonding

RBSN: Reaction sintered silicon nitride
HPSN: Hot-pressed silicon nitride

Figure 6. Designs for a fully-ceramic wheel.

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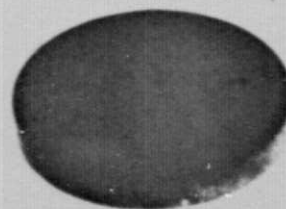


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Hot Pressed
Si₃N₄ Hub



Hot Pressed Hub
Bonded With Reaction
Sintered Si₃N₄ Ring



Hot Pressed Si₃N₄ Hub
Bonded With Reaction
Sintered Si₃N₄ Blade Ring

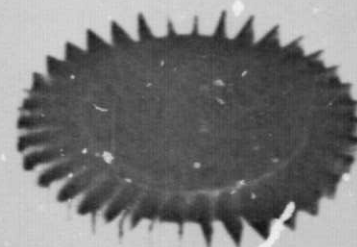


Figure 7: Cement Bonded Prototype Rotors

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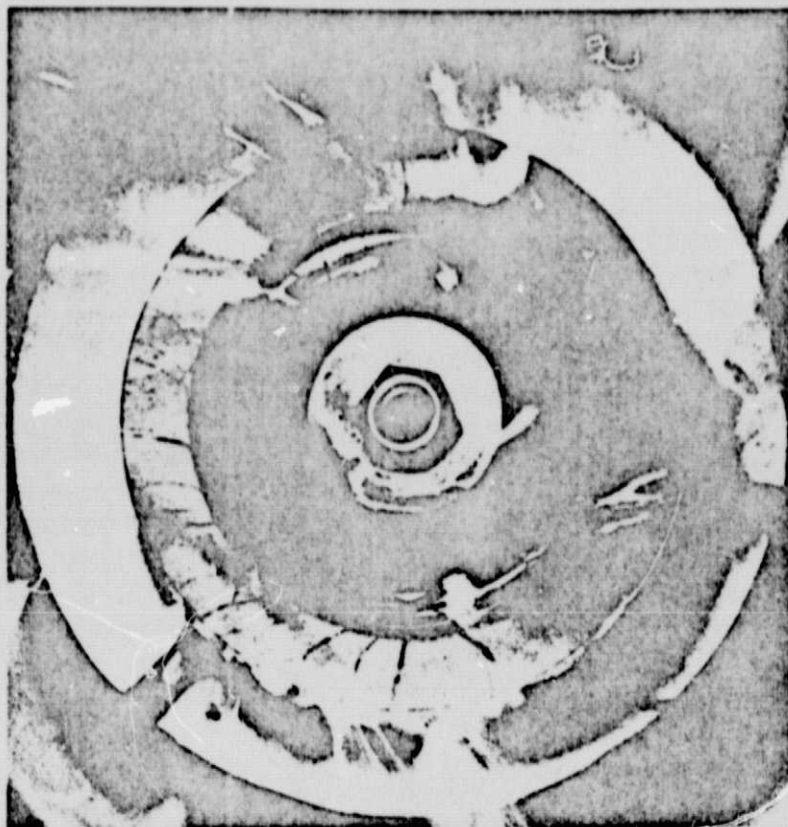


Figure 8: Si₃N₄-Post Hot-Pressed Prototype Rotor, $u_m = 385$ m/s

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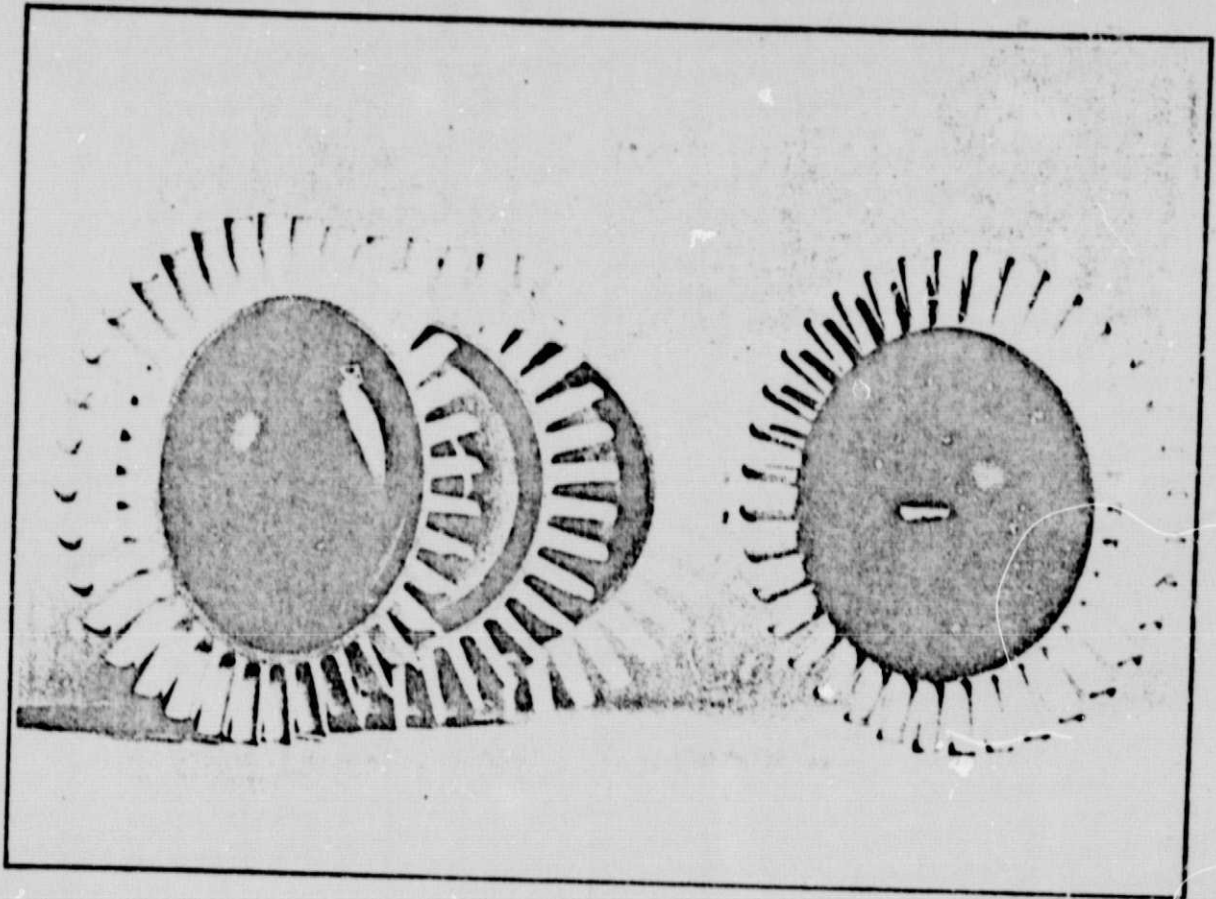


Figure 9: Totally Ceramic Turbine Wheels, Position 9-1-77

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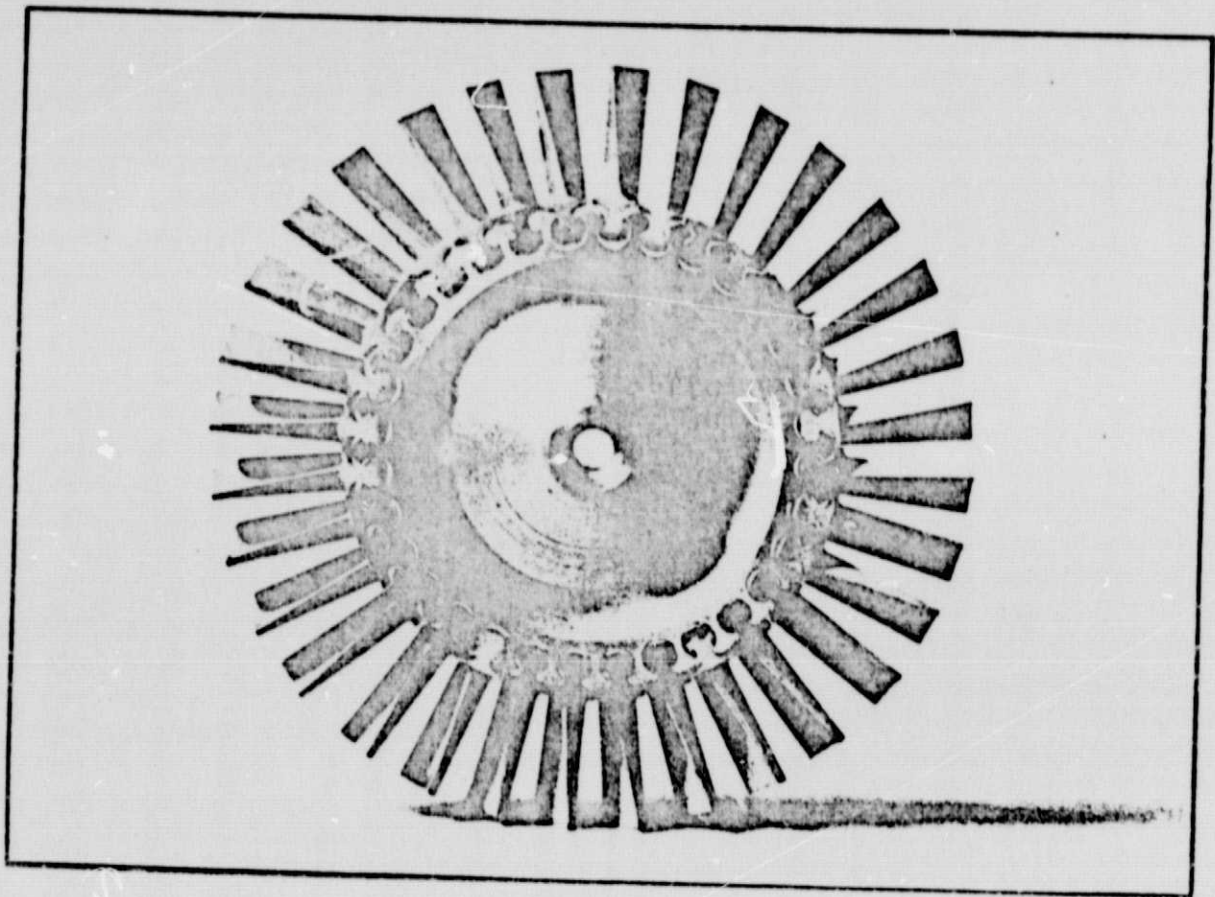


Figure 10: Turbine Wheel with Metal Hub and Ceramic Individual Blades